# CAPTURE OF CARRIERS TO SCREENED CHARGED CENTRES AND LOW TEMPERATURE SHALLOW IMPURITY ELECTRIC FIELD BREAK DOWN IN SEMICONDUCTORS

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**Abstract**

Free carrier capture by a screened Coulomb potential in semiconductors are considered. It is established that with decreasing screening radius the capture cross section decreases drastically, and it goes to zero when $r_s = a_B^*$. On the basis of this result a new mechanism of shallow impurity electric field break down in semiconductors is suggested.

## 1 INTRODUCTION

For correct consideration of the kinetic, photoelectrical and optical phenomena in semiconductors and semiconductor structures it is necessary to take into account the carrier capture by attractive centres. One of these centres in semiconductors are negatively or positively charged shallow acceptors or donors, the potential of which is considered usually as a Coulomb interaction. The capture of carriers by a Coulomb centre in semiconductors was

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first considered by Lax [1] and was corrected in [2]. In [2] the capture theory was developed for small and large concentrations of impurities. In the first case the capture occurs at isolated centres . In the second case, which is characterised by an overlap of the effective capture orbits ($r_T = e^2/\chi kT$) of neighbouring centres, it was supposed that the capture takes place in the wells of the potential fluctuations of impurities. This gives an essentially week dependence of the capture cross section (CCS) on centres concentration ($\sigma \tilde{} N_d^{1/6}$) compared with that for isolated centres ($\sigma \tilde{} N_d$). However, he potential of the charged impurity in real semiconductors may be considered as purely Coulombic in the week doping case only ($N_d^{1/3} \cdot a_B^* \ll 1$,where $N_d$ is the shallow impurities concentration, $a_B^*$ is an effective Bohr radius).With increasing of impurity concentration the potential of charged centre changes from a Coulomb to a Yukawa type potential as a result of screening by free electrons and charged impurities.

In this work we will consider the capture process in the case of a high free carrier concentration $n$, when Debye screening of a Coulomb centre takes place. Such a situation can be realized in semiconductors under the following circumstances:

-in the case of high impurity concentration and at relatively high temperatures when $kT$ is comparable with the shallow impurity ionization energy $\epsilon_i$, so that most of shallow impurities are ionized ($n \tilde{} N_d$);

-in the case of small as well as high concentrations of impurities and low temperatures ($kT \ll \epsilon_i$), if a sufficiently strong electric field is applied to the semiconductor. As it is known [2-3] the CCS would decrease under the electric field, and as a result free electron concentration would increase [4]. As it will be shown in the case of strong free electron screening the CCS goes to zero.

# 2 CAPTURE CROSS SECTION TO SCREENED COULOMB CENTRE

We consider the capture of free carriers by a potential of the form

$$U = -(e/\chi r)\exp(-r/r_s) \tag{1}$$

In (1) $r_s$ is the Debye screening radius, and it must be chosen as $r_s =$

$\chi \cdot \mathbf{E}_F/(6\pi ne^2)$ in the degenerate case and as $r_s = \sqrt{\chi kT/(4\pi ne^2)}$ in the nondegenerate case, where $\mathbf{E}_F = h^2k_F^2/2m^*$, $k_F = (4\pi n^2)^{1/3}$, $\chi$ is dielectric constant and $n$ is the free carrier concentration.Note that in the conduction band bottom of gap semiconductors the carriers distribution can be taken as Boltzman one also in low temperature and high concentration case.

Similar to Coulomb potential case, the effective capture radius of centre is determined from the equation

$$\mathbf{E} = (e^2/\chi r) \cdot \exp(-r/r_s) \tag{2}$$

where $\mathbf{E}$ is the total energy of the carriers. In contrast to Coulomb potential case equation (2) is transcendental, and can not be solved analytically.

To calculate the CCS we use the following expression [2]:

$$\sigma = (\pi h)^2/(2kTm^\star) \left[ \int_{-\infty}^{0} \exp(\mathbf{E}/kT) B^{-1}(\mathbf{E}) d\mathbf{E} \right]^{-1} \tag{3}$$

where

$$B(\mathbf{E}) = \int \epsilon \tau^{-1}(\epsilon) \rho(\epsilon) \delta \left[ \mathbf{E} - \epsilon - U(r) \right] d\epsilon d^3r \tag{4}$$

$$\rho(\epsilon) = 8\sqrt{2}\pi(2\pi h)^{-3} m\star^{3/2} \epsilon^{1/2}, \tau(\epsilon) = l_0 (m\star/(2\epsilon))^{1/2}, l_0 = (\pi h^4 \rho_0)/(2m\star^3 \mathbf{E_c^2}) \tag{5}$$

$\mathbf{E_c}$ is the deformation potential constant,$\rho_0$ is the crystal density, $m^\star$ is the carrier effective mass.At low temperatures electrons are distributed between the impurity ground state $1s$ up to conduction band bottom. In such a situation carriers can not be captured by emission of an optical phonons because theirs energy is greeter than distances between shallow impurity states (at least for most of semiconductors). For this reason formula (3) describes capture owing to diffusion lowering of carriers as a result of their wandering between excited states of impurity by absorption or emission of acoustic phonons only.

Substituting (1) and (5) into (4) and after integrating using $\delta$-function properties, it is easy to obtain for $B(\mathbf{E})$ an expression.

$$B(\mathbf{E}) = 8m^\star/(\pi l_0 h^3) \left[ \frac{1}{3}\mathbf{E}^2 r_i^3 + 2\mathbf{E}^2 r_i r_s^2 (1 + \frac{r_i}{r_s} - e^{\frac{r_i}{r_s}}) + \frac{1}{2}\mathbf{E}^2 r_i^2 r_s \left( e^{\frac{r_i}{r_s}} - 1 \right) e^{\frac{r_i}{r_s}} \right] \tag{6}$$

The expression for $B(\mathbf{E})$ can be written in the form:

$$B(\mathbf{E}) = 8m\star/(\pi l_0 h^3)\cdot r_s^3\mathbf{E}^2/6\cdot J(x) \tag{7}$$

$$J(x) = 2x^2 + 12x(1+x-\exp(-x)) + 3x^2(\exp(x)-1)\exp(x) \tag{8}$$

where $x = r_i/r_s$, $r_i$ is the root of equation (2) for a given screening length $r_s$. Note that in obtaining (6) and (7) for each $r_s$ we first find $r_i$ numerically from (2), and then substitute this value as an upper limit of the integral (4).

Substituting (6) and (7) into (3) we obtain an expression for CCS

$$\frac{\sigma_0}{\sigma} = 2/(kT)^2\cdot(e^2/\chi r_s)^3\int\limits_0^\infty \exp(-\mathbf{E}/kT)/(\mathbf{E}^2 J(x))\cdot d\mathbf{E} \tag{9}$$

where

$$\sigma_0 = (4\pi/3l_0)\cdot(e^2/\chi kT)$$

is the CCS in the Coulomb potential case.

The results of numerical calculation of $\sigma_o/\sigma$ dependence on $r_s/a_B^*$ at $T = 4.2K$ for $GaAs$ (curve 1) and $Ge$ (curve 2) with parameters $m^\star = 0.067m$, $\chi = 12.5$ and $m^\star = 0.082m_0$, $\chi = 16$, respectively, are shown in Fig.1.

It is easy to show that when $r \to \infty$ for CCS from equation (8) the Coulomb potential case is obtained. Note, that the screened potential (1) in contrast to the Coulomb one has finite number of bound states, and when $r \le a_B^\star$ has no bound states at all -they pass into the continuous bands [5,6]. It is obvious that in the absence of bound states the CCS must be equal to zero for such a centre. But as it is seen from Fig. 1 when $r_{s=}a_B^\star$ the CCS in comparison with Coulomb potential case decreases no more than 20 and 25 times for Ge and GaAs correspondingly. This means that the diffusive method used for the CCS calculation in [2] and in this work becomes inapplicable at small screening lengths, when the number of discrete states is small. In this case the capture process can not be considered as a diffusive lowering of carriers through energetic states of impurity. Note that owing to this the values of $\sigma_o/\sigma$ would be higher than those presented by curves 2 and 3 not only for $r_{s=}a_B^\star$.

Thus we obtain the simple result -the more the screening the less is the capture coefficient, and when $r_{s=}a_B^\star$ it is equal to zero. It is obvious that the analogous result must be obtained for the coefficient of thermal ionization from impurity states because of the lowering of the ionization energy $\epsilon_i$ from

them when screening is strong (ionization probability $w_i \sim \exp(-\epsilon_i/kT)$). Now we will consider some consequences of the obtained result.

# 3 LOW TEMPERATURE SHALLOW IMPURITY ELECTRIC FIELD BREAK-DOWN MECHANISM

We will discuss the low temperature shallow impurity electric field breakdown ( LTSIEFB) phenomenon in semiconductors. From the first observations of LTSIEFB [7] up to now [8] it is believed that this phenomenon is only due to impact ionization of neutral impurities by free electrons as a result of their heating under an external electric field. Our result allows to put forward an alternative mechanism for LTSIEFB which explains all peculiarities of current voltage characteristic (CVC) of semiconductors including avalanche-like increase of current and " S "-like form of CVC at breakdown electric field. According to this mechanism with increasing of electric field the concentration of free carriers $n$ will increase because of well knowing decrease of capture coefficient $\alpha$ and increase of ionization coefficient $\beta$.The value of $n$ in electric field would be established by balance condition between capture and thermic ionization - $n\alpha N_D^+ = \beta N_D^o$ ($N_D^o$- neutral and $N_D^+ = N_A + n$-charged donors concentrations)

$$n(E) = N_D^o(E)/N_D^+(E) \cdot \beta(E)/\alpha(E) \tag{10}$$

At some electric field, which is very close to the breakdown one, the value of $n$ would be so much that the screening of charged impurities will take place. From this moment an avalanche increase of free carrier concentration will begin, owing to the CCS decrease because of screening and, as a result of this, a further increase of $n(E)$, and so on. Thus $n(E)$ and as well as

$$j(E) = en(E)\mu(E)E \tag{11}$$

-dependencies will show an avalanche-like increase with electric field. Note that LTSIEFB takes place at low temperatures when the dominant scattering mechanism of carriers are charged impurities. This means that

owing to the screening of charged impurity potentials, the mobility of carriers $\mu(E)$ at the breakdown electric field will increase, and as a result of this the CVC would have an "S"-like character. Screening induced $\mu(E)$ increase causes an additional (besides of $n(E)$) current increase in the avalanche-like region of the CVC. Note that it was already established from cyclotron resonance line shape investigations of $n-GaAs$ that free carrier screening of charged impurities is strong at the breakdown electric fields [9-10].For LTSIEFB there is no need for the condition $r_s = a_B^*$, when total screening of impurity state occurs. First of all such a condition means all neutral shallow impurities to be ionized in semiconductor. But as it was shown from Hall measurements [11] at breakdown electric field in $n-Ge$ only 5% and, from plasma shift of cyclotron resonance line in $n-GaAs$ [12] at electric fields 3-times greater than the breakdown one, only about 40% of neutral impurity were ionized. On the other hand the condition $r_s = a_B^*$ corresponds also to a Mott transition which occurs at sufficiently high impurity concentrations -$N_D^{1/3} a_B^* \approx 0,25$ and in this case all impurity electrons are in the conduction band [13]. Hence LTSIEFB must disappear at very high impurities concentrations. Note that according to the screening mechanism of LTSIEFB it must disappear in the low impurity concentration case too, which can be determined from the condition $r_s = r_T = e^2/\chi kT$. Consequently, according to the supposed mechanism, LTSIEFB takes place only at neutral impurity concentrations $(\chi kT/e^2)^3 \cdot (1/4\pi) < N_D^o < (0.25/a_B^*)^3$. For $n-GaAs$ this condition requires $5 \cdot 10^{11} cm^{-3} < N_D^o < 2 \cdot 10^{16} cm^{-3}$. In the next work I will present an experimental evidence which contradicts the impact ionization model and confirms above mechanism of LTSIEFB in $n-GaAs$. The fact that the CCS goes to zero when $r_s \leq a_B^*$ may be considered as one of reasons for a Mott transition in semiconductors.

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Fig. 1. Dependence of s0/s on screening radius rS/aB*: 1 - for GaAs; 2 - for Ge; 3 - Coulomb potential case.

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